# Manipulation of high energy electrons with a nano scale lens

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## Motivation

Traditional magnetic lenses

To find a **small lens** to modulate the electron beam

electrons

a new small lens

$$\mathbf{E} = \frac{\Delta V}{\Delta x}$$ Decrease the distance

Create a **nano size hole** in amorphous carbon(a-C) to generate strong electric field to divergent electrons

Electrons    Rays

Hole in aC    Concave lens
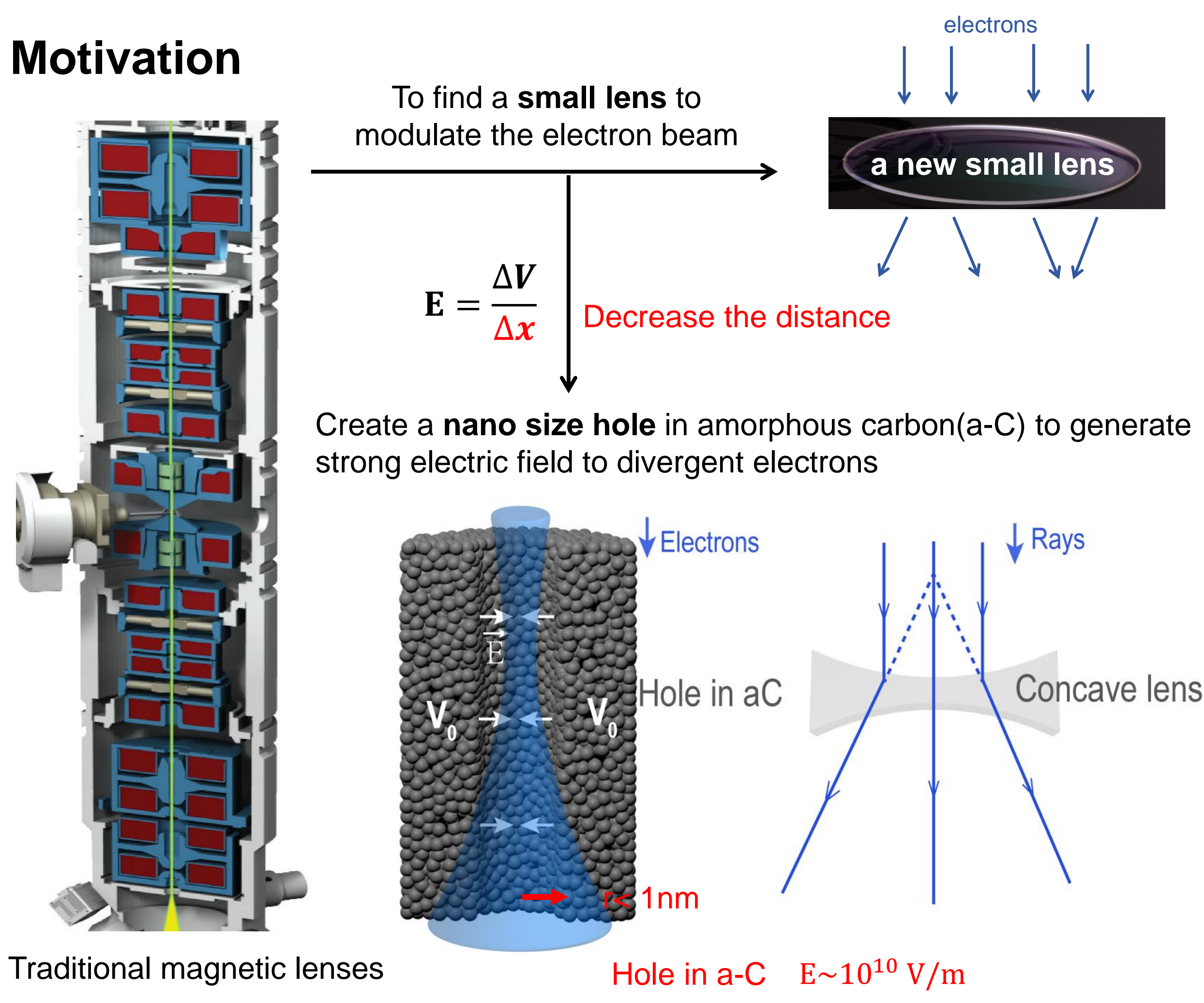
$V_0$    $V_0$

$r \approx 1nm$
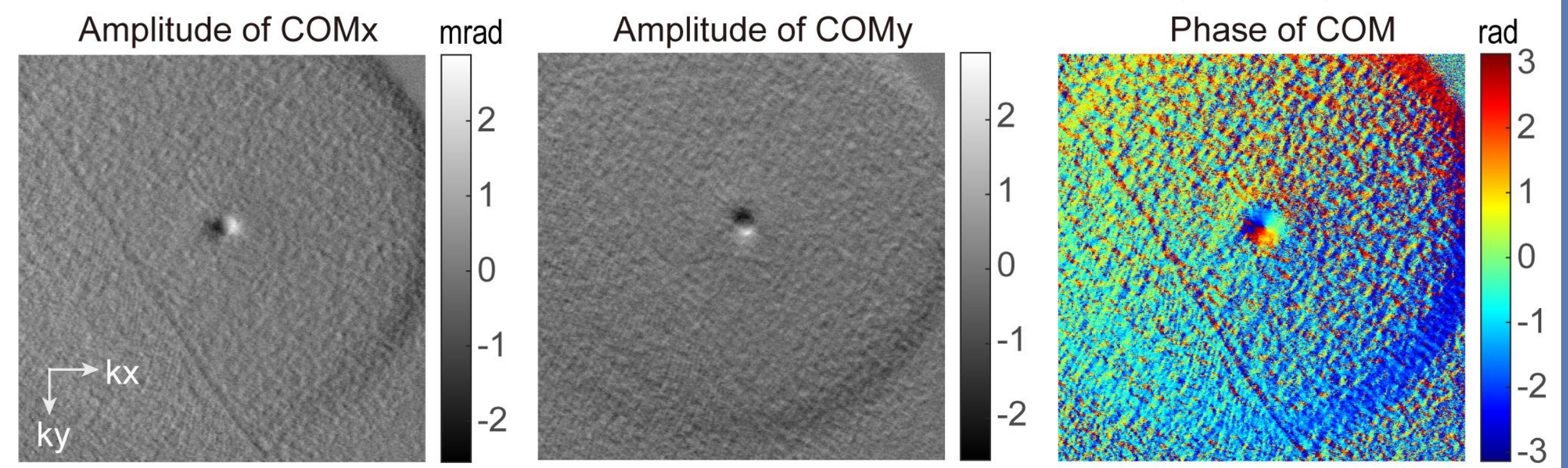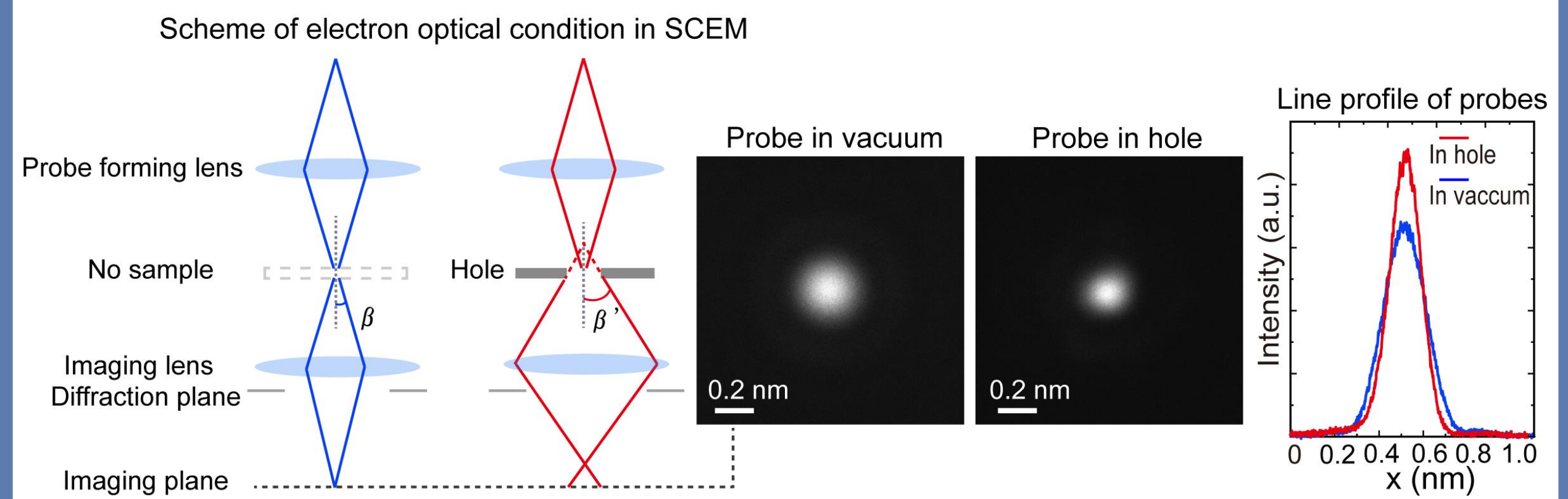
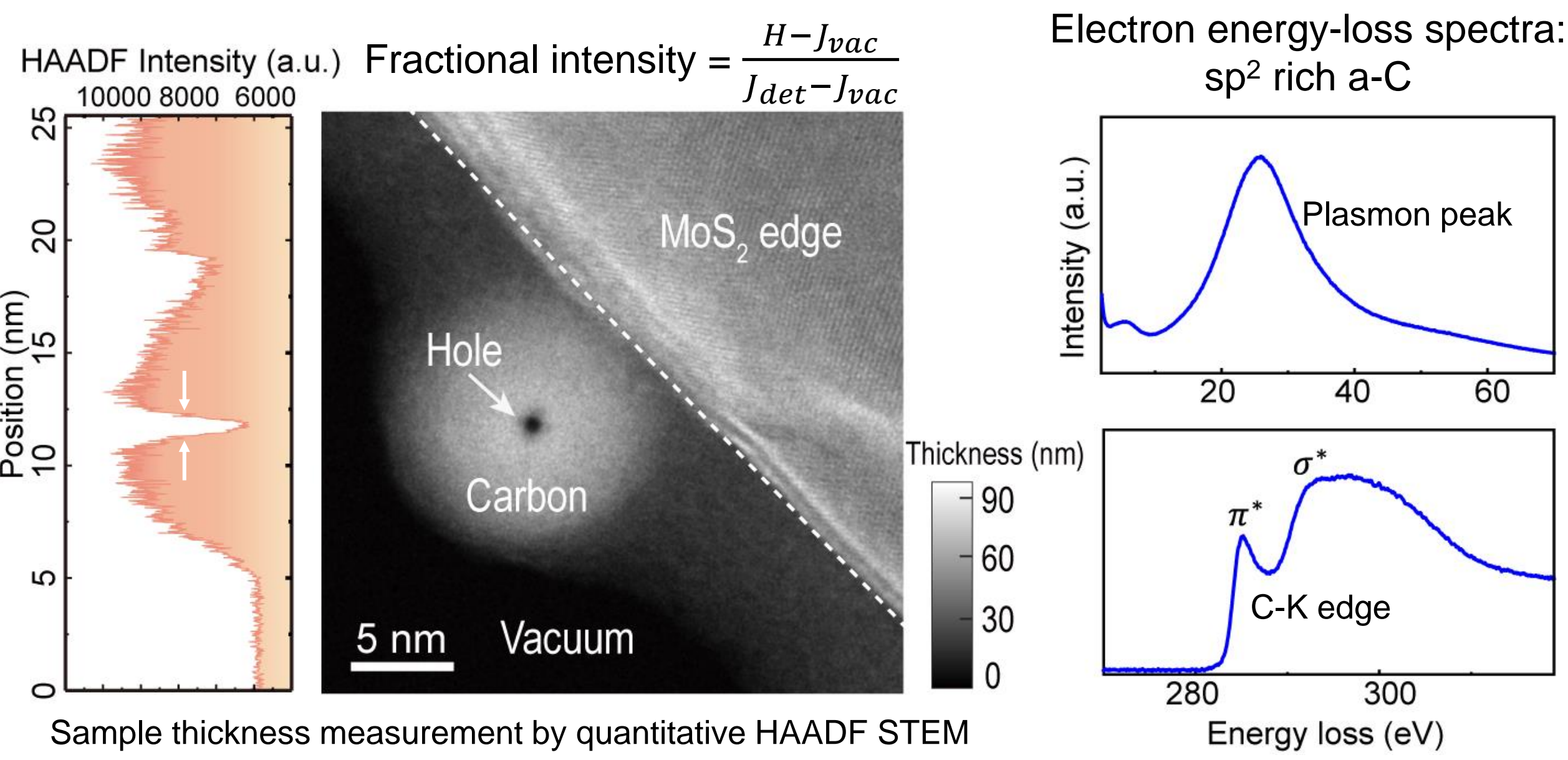Hole in a-C    $E \sim 10^{10}$ V/m

## Centre of mass / Differential phase contrast

$$I_D(\vec{k}, \vec{r_p}) = \left|\psi_D^{STEM}(\vec{k}, \vec{r_p})\right|^2 = \left|\{\psi_{in}(\vec{r})\}(\vec{k}) \otimes \mathcal{F}\{\exp[-i\sigma E_z \cdot (\vec{r} + \vec{r_p})]\}\right|^2 = \left|\psi_{in}\left(-\vec{k} - \frac{\sigma E_z}{2\pi}\right)\right|^2$$
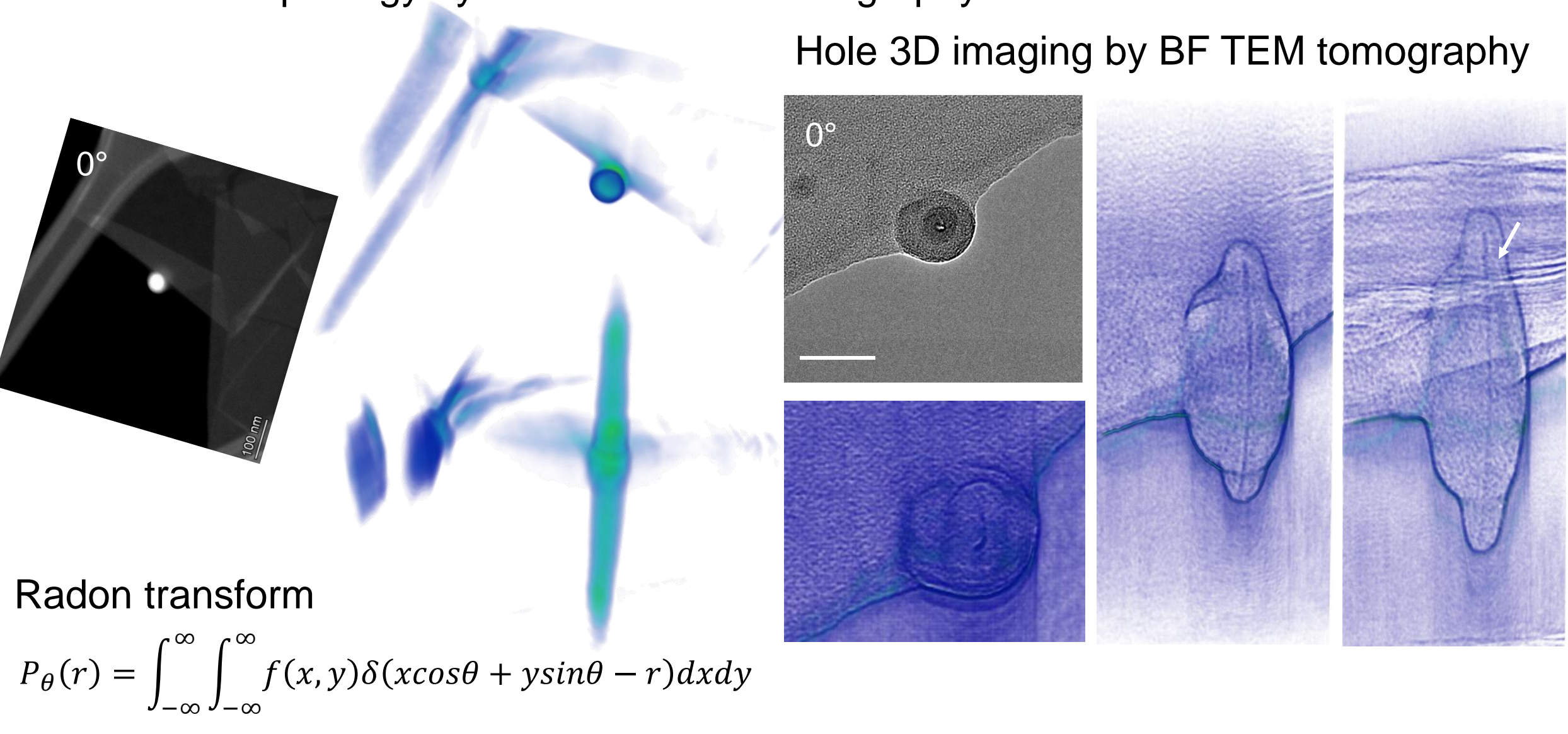
Amplitude of COMx    mrad

Amplitude of COMy    mrad

Phase of COM    rad

kx
ky

## SCEM diagram and refocus effect in experiment

Scheme of electron optical condition in SCEM

Probe forming lens

No sample    Hole

$\beta$    $\beta$

Imaging lens
Diffraction plane

Imaging plane

Probe in vacuum    Probe in hole

0.2 nm

Line profile of probes

In hole
In vacuum

Intensity (a.u.)

0 0.2 0.4 0.6 0.8 1.0
x (nm)

## 3D Morphology and spectroscopy of hole in carbon

HAADF Intensity (a.u.)    Fractional intensity $= \frac{H - J_{vac}}{J_{det} - J_{vac}}$

10000 8000 6000

Position (nm)

MoS$_2$ edge

Hole

Carbon

5 nm    Vacuum

Thickness (nm)
90
60
30
0

Sample thickness measurement by quantitative HAADF STEM

Electron energy-loss spectra: sp$^2$ rich a-C

Intensity (a.u.)

Plasmon peak

20    40    60

$\pi^*$    $\sigma^*$

C-K edge

280    300
Energy loss (eV)

Carbon 3D morphology by HAADF STEM Tomography

0°

Radon transform

$$P_\theta(r) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\delta(x\cos\theta + y\sin\theta - r)dxdy$$

Hole 3D imaging by BF TEM tomography

0°

## Multi-slice MIP simulations of electron propagation

Incident wave

TEM sample    divided into slices

Exit wave

Incident wave
Transmit
Propagate
Transmit
Propagate
Transmit
Propagate

$t_n(x,y)\Psi_n(x,y)$
$\Psi_{n+1}(x,y) = p_n(x,y,\Delta z) \otimes t_n(x,y)\Psi_n(x,y)$

Transmit
Exit wave

Electron probes

Probe propagation cross section
Through vaccum    Through hole

depth (nm)

-1 -0.5 0 0.5 1
x (nm)

-1 -0.5 0 0.5 1
x (nm)

Probe back in Confocal plane
In vacuum    In hole

0.2 nm    0.2 nm

Line profile of probes

In hole
In vacuum

Intensity (a.u.)

-0.5    0    0.5
x (nm)

Probe in exit plane

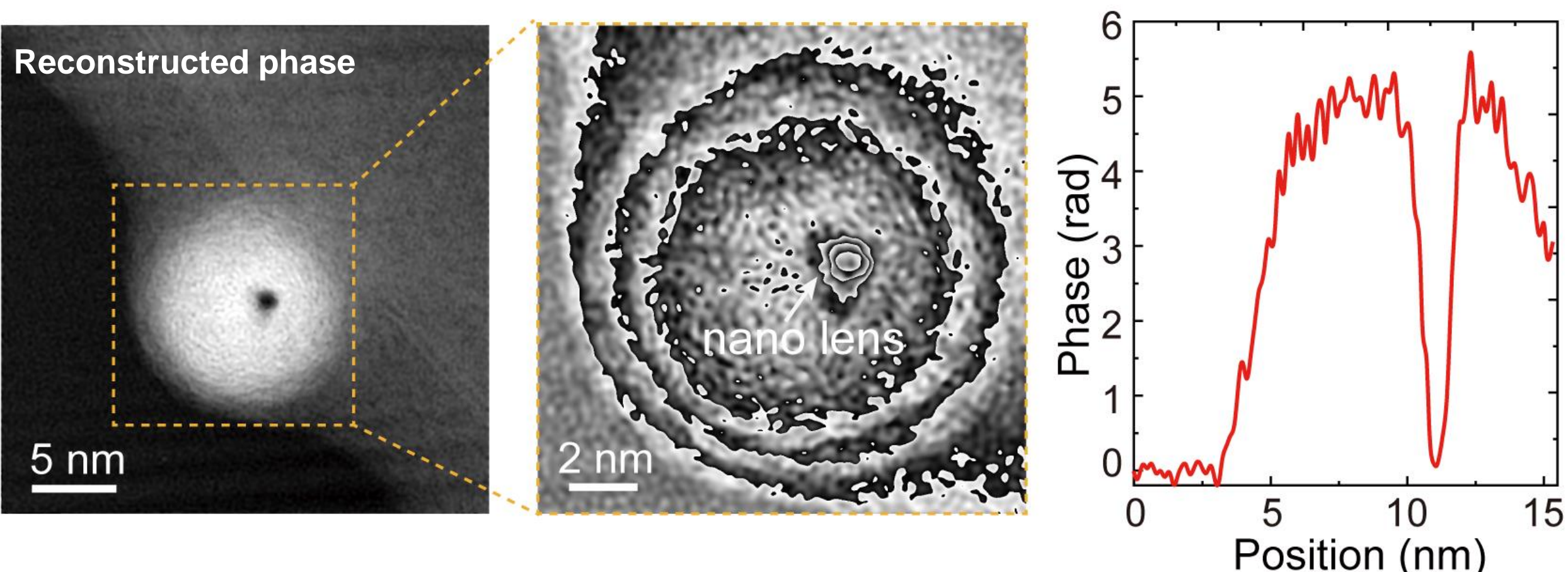0.2 nm    0.2 nm

Holes with different cross section shapes

## Phase shift induced by hole

$$\Phi(r) = C_E \int_{-\infty}^{+\infty} V_0(r,z)dz - \frac{e}{\hbar}\int_{-\infty}^{+\infty}\int_{r}^{+\infty} B_n(\rho,z)d\rho dz$$

Off axis electron holography

$$I(r) = |\psi_o(r) + \psi_r(r)|^2 = 1 + A^2(r) + A(r)e^{i\phi(r) - 2\pi i q_c r} + A(r)e^{-i\phi(r) + 2\pi i q_c r}$$

Reconstructed phase

5 nm

nano lens

2 nm

Phase (rad)

6
5
4
3
2
1
0

0    5    10    15
Position (nm)

## Probe travels backwards and forwards

0.2 nm

References: Phys. Rev. Lett. **112**, 166101. Phys. Rev. Lett. 119, 174801. Nature Physics.8(2012). Reports on Progress in Physics 71(1):016102. Ultramicroscopy. 178 (2017).